On the measurement of transverse shear stress on a rectangular open channel using optimal Preston tube

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Abstract

The laboratory studies have been carried out in this research. Determining the sensitivity analysis of the Preston tube diameter in shear stress, four Preston tubes with external diameters of 3.2, 3.9, 4.7 and 6.3 mm were used. The aspect ratios of 2.86 to 13.95 were examined. For measuring the pressure difference of the Preston tube a 200 millibar differential pressure transducer with 0.01 accuracy of the original scale was used. Laboratory results demonstrated that Preston tubes with a diameter of 3.9 mm present the minimum difference in the average value of the shear stress resulting from the Bechert and Patel calibration equations. Therefore, using the Preston tube with an optimal diameter, transverse distribution of shear stress in channels bed and wall were determined. The outcome of this part of study is two dimensionless relationships for determining the local shear stress both in the bed and wall. These relationships are a function of the aspect ratio $B/H$ and the bed relative coordinates $b/B$ in cross section and $Z/H$ sidewall. The survey showed that the dimensionless bed shear stress distribution is considerably influenced by the aspect ratio. The transverse distribution of wall shear stress is independent from the aspect ratio for $B/H>3$.

Keywords: shear stress, Preston tube, differential pressure, transducer, aspect ratio

1-1 Introduction

In uniform flows, the friction force is always equal to that effective component of gravity force which is in the direction of the fluid flow. The frictional force per wetted perimeter unit in a channel, is called shear stress. It is plausible that the transverse distribution of shear stress in wide and broad channels is not uniform. Determination of the boundary shear stress and its distribution along the wetted perimeter is a fundamental issue in open channels flow. Shear stress distribution is primarily affected by secondary flows, sediment transport rate, erosion or sedimentation, and geometry of the channels. The shear stress distribution and flow resistance in both simple and compound channels with smooth and rough surfaces have been studied by many researchers.

Olsen and Florey [1] studied trapezoidal, rectangular, and triangular sections using finite difference methods and analytical approaches. These studies showed that the distribution of frictional
force varies depending on the cross-section shape but cross-section size in terms of the frictional force
distribution is non-effective. The aforementioned results also showed that the bed maximum frictional
force is close to the theoretical stress amount resulting from the channel slope. While this force in
channel walls is limited to about 0.76 of $\gamma HS$.

Ghosh and Roy [2] using a method called three-point suspension system, directly measured the
shear stress in rectangular and trapezoidal open channels with smooth and rough beds. Their results
showed that shear stress distribution around the wetted perimeter is non-uniform.

Kartha and Leutheusser [3] have conducted a series of experiments on the determination of boundary
shear stress distribution to design stable alluvial channels by tensile forces. Experiments were
performed in a rectangular laboratory flume with smooth-wall in aspect ratios between 1 and 12.5.
They measured shear stress by Preston tube. For calibration of Preston tube the indirect method was
applied and the law of the wall and velocity logarithmic distribution was used. At that time, they
indicated that none of the analytical available techniques can calculate the shear stress for a proper
design of alluvial channels.

Knight and Patel [4,5] performed a number of experiments to calculate the shear stress distribution on
a rectangular channel with smooth bed at aspect ratios of 1 to 10. They found that the number and
shape of the secondary flow cells have a different distribution in different aspect ratios. In this study,
multiple pairs of clockwise or anti-clockwise secondary flow cells were observed. They also reported
maximum and average shear stress in different aspect ratios. The interaction among of secondary
flows and shear stress distribution are shown in Fig. 1.

Fig 1. Interaction between secondary flow cells and shear stress distribution in the different
aspect ratios, Knight and Patel [4,5]

Knight et al [6] carried out experiments on channels with homogenous and heterogeneous roughness
and presented equations to determine the average and maximum shear stress on the bed and wall.
These equations are presented as a fraction of the total shear force, and include aspect ratio, the walls
slope and relative roughness. They found that the percentage of the wall shear force will be reduced by
increasing of the $P_I/P_w$ and $K_{sb}/K_{sw}$.

Conducting sensitivity analysis of Preston tube diameter Sutardi and Ching [7] showed that when
the ratio of Preston tube diameter to boundary layer thickness is 0.048, and the pressure gradient is
zero, the pipe with a 3.23mm diameter has the least difference in determining the flow resistance

Ardıçlioğlu et al. [10], conducted an experimental study for the shear stress distribution
throughout the entire length of the cross-section in fully developed boundary layer area, in an open
rectangular channel, in both smooth and rough surface. By measuring the speed in both smooth and
rough surfaces, they conducted 48 tests. Using logarithmic distribution of velocity, the average shear stress in the cross section for aspect ratios of 4.2 to 21.6 and the Froude numbers of .12 to 1.23 were measured. The results for smooth and rough surfaces, respectively are shown in the following relations.

Smooth surface
\[ \tau_m = -0.043 - 0.053b/h + 2.06Fr \]  

Rough surface
\[ \tau_m = -0.019 - 0.013b/h + 5.86Fr \]

Their study led to introduce a second order polynomial for determination of the shear stress distribution along the cross-section.

\[ \frac{\tau_0}{\tau_m} = 0.24(2y/b)^2 + 0.007(2y/b) + 1.079 \]

Where \( \tau_0 \) is the total shear stress and \( \tau_m \) is the local shear stress.

Knight et al [11] using a method called SKM, present a simple model to predict the depth-averaged velocity and shear stress in trapezoidal channels under the presence of the secondary flow. Extensive range of shear stress data were used validating the model. Results showed that the transverse velocity derived from this approach is consistent with field observations, while the adjustment for boundary shear stress does not always exist.

Lashkar-Ara et al. [12] used the Preston tube and utilized the indirect method to measure the average local shear stress of bed and wall of smooth rectangular channels. Lashkar-Ara and Fathi-Moghadam [13] directly measured the shear stress in smooth rectangular channels and introduced a so-called knife edge flume method. The flume was equipped by load cells in such a way that has the ability to measure the total shear force exerted on the wetted perimeter. For the separation of bed and wall shear stress position, the Preston tube with outer diameter of 4 mm was used. To convert the static and dynamic pressure difference recorded in the Preston tube to the shear stress, the Patel calibration curve was used. The results of their research showed that direct and indirect methods of shear stress management have 4 and 8% error, respectively, in comparison with theoretical equations.

Haifeng et al [14] designed a micro floating element shear stress sensor. This micro-fabricated floating element sensor was developed to measure the shear stress in laminar flow channels. The sensor with dimensions of \( 4 \times 3 \times 0.5 \text{ mm}^3 \) was fabricated by inductively coupled plasma (ICP) etching techniques with single mask. They designed three layers packaging strategy to reduce parasitic capacitance and realized flush mounting with the wall. Their experiments showed that this prototype sensor can measure shear stress of at least 35 Pa with sensitivity of 27 mv/Pa. The linearity was measured to be 3.4% while the repeatability was 4.9%.

Devi and Khatua [15] predicted depth-averaged velocity and the boundary shear stress distribution of a compound channel based on the mixing layer theory. Their analytical solution eventuated in the
Shiono Knight Method have solved considering a new panel of shear layer width at the junction. They conducted a reliable experimental measurement for quantification of the shear layer width and to procure the new calibrating coefficients for secondary flow and friction factor. The model is found to provide satisfactory results when applied to experimental, FCF channels and natural river data sets. 

Park et al. [16] directly measured of bottom shear stress under high-velocity flow conditions to achieve high-velocity flow conditions; a laboratory-scale flume has been specially made in which flow velocity can reach over 3ms\(^{-1}\). Also, an instrument that can directly measure bottom shear stress has been developed and validated. The newly-built flume can achieve the Reynolds number that is comparable to those in flooding rivers when it is based on the local water depth near the revetment blocks.

Shan et al. [17] used a simple method to estimate the bed shear stress in smooth and vegetated compound channels, based on the Darcy-Weisbach equation. This method contains a dimensionless parameter \(A_i\), to represent the relationship between the bed shear stress and the velocity close to the channel bed \((U_b)\), which is determined in each divided domain. This method is verified in two smooth compound channels with different geometries, and in one compound channel with emergent floodplain vegetation. The comparison of predicted and measured bed shear stresses indicates the good predictive capability of this method, particularly in the mixing region.

Sheikh Khozani et al. [18] using five different methods to estimate the shear stress distribution in compound channels. Methods proposed by Yang and Lim (YLM) [19], Khodasheans and Paquier (KPM) [20], Sterling and Knight (SKM) [21], Zarrati et al. (ZAM) [22] and Bonakdari et al. (BAM) [23] are compared with experimental data. They concluded that ZAM showed more accurate results than BAM, however BAM required solving much fewer equations than ZAM and presented more accurate results than other geometric methods. Among all models, BAM is proposed as a simple and accurate model for predicting the shear stress distribution in compound channels.

Mohammadi [24] conducted several measurements to explore the hydraulic characteristics of a V-shaped bottom channel. He used propeller for point-wise velocity measurements. The result show that the lateral variations of depth averaged velocities indicate that the velocity distributions are almost symmetrical about the cross sectional centerline, except for some flow cases, in which there are slight deviations, despite the fact that the flow condition was uniform for all cases. Also It was found that the widely used log-law for the vertical profile of velocity does not appropriately model the velocity distribution in this particular channel shape. Considering the results obtained for the span- and depth-wise velocity distributions, especially the distortion of the isovels and the location of maximum velocity, there are strong evidences of secondary currents that are present in this channel cross section.

Previous studies have denoted that various parameters like aspect ratio, roughness, secondary flow, and eddy viscosity affect the transverse distribution of shear stress. The aim of this study can be considered from two perspectives. Firstly, according to previous studies, the local shear stress resulting from the Preston tube is sensitive to its pipe diameter. Secondly, aspect ratio is effective on
the number of secondary flow cells. The simultaneous effect of both of these two parameters on the transverse distribution of wall shear stress has not been discussed yet in previous studies. Therefore, to present the governing equation of the shear stress on the bed and wall of flat rectangular channels this experimental research aims to study the transverse distribution of shear stress based on the Preston tube diameter sensitivity analysis.

1-2-Methodology

In this research, a 10-meter length flume with 60 cm width and 70 cm height is used in the hydraulics model and river engineering laboratory of Jundi-Shapur University of Technology, Dezful, Iran to determine the transverse distribution of shear stress based on the sensitivity analysis of the Preston diameter. To this end, four Preston tubes with external diameters of 3.2mm, 3.9mm, 4.7mm, and 6.3mm were used to determine the local shear stress on the channel bed. Assuring the development of the boundary layer, eleven measurement stations were installed each 30 cm into the flume. The location of the stations and the schematic of the experimental system is illustrated in fig 2.

Fig 2. Experiment schematic

Using momentum integral equation for the flow in a zero-pressure gradient and concerning Prandtl’s one-seventh power law for modeling the velocity index in turbulent flow on smooth surfaces, boundary layer thickness and wall friction coefficient can be determined in the center of the flume floor in all of the stations with equation 4 and 5.

\[
\frac{\delta}{x} = \frac{0.382}{Re_x^{1/8}} \tag{4}
\]

\[
C_f = \frac{2\tau_b}{\rho U^2} \tag{5}
\]

where \(\delta\) is the Boundary Layer thickness, \(x\) is the station distance from the beginning edge of the flume, \(Re_x\) is the length Reynolds number, \(\tau_b\) shear stress, \(\rho\) is the fluid density, \(U\) is the velocity and \(C_f\) is the wall friction coefficient. The value of the shear stresses in the centre of channel for all 11 stations was then determined.

The values of static and total pressure difference in various aspect ratios of \(B/H\) were measured and reported using pressure transducer apparatus with a capacity of 200 mill bar and 50 Hz measuring frequency. In order to create uniform flow condition and to match the hydraulic gradient with the flume bed slope a weir at the end of the flume was installed.
By changing the flow rate resulting in different aspect ratio values, the static and total pressure difference were measured in each of the Preston tubes. Then, using the Patel and Bechert equations, the shear stresses in all 11 stations were measured. By comparing relative differences of shear stress values resulting from both methods Patel and Bechert, the possibility to suggest an optimal Preston tube diameter in determining the local shear stress was provided. After determining an optimal Preston tube diameter, the shear stress of the bed and wall of the channel was calculated. For this purpose, the Preston tube was moved in the vicinity of wall and bed, using a two-dimensional movable seat. And then the values of static and total pressure difference in each aspect ratio was measured and reported.

1-3-Results and discussion

1-3-1-Sensitivity analysis

All measurements were performed in the range of 11.06 to 102.38 liter per second flow rate. Flow rate variations led to observable changes in water depth ranging from 4.3 cm to 21 cm and the aspect ratios of 2.86 to 13.95. As previously noted, from the aspect of the sensitivity analysis of the Preston tube diameter in determining the shear stress, four Preston tubes with external diameters of 3.2, 3.9, 4.7, and 6.3 mm were used. For each aspect ratio, Preston tube static and total pressure difference values using four different diameters, was marked, measured and recorded in all eleven stations. Then, using the Patel and Bechert calibration equations, local shear stress was calculated and results were compared. Reynolds numbers in all trials were changed in a range of $6.4 \times 10^4$ to $39.87 \times 10^4$, indicating that this research was performed under the turbulent flow condition. In order to determine the hydraulic gradient, depth and velocity values were measured in consecutive sections with a one-meter distance between. A Pitot tube was used for measuring the velocity. After determining the hydraulic gradient between the sections and drawing its profiles, the average hydraulic gradient was then calculated. An average hydraulic gradient of $1.2 \times 10^{-3}$ was estimated in all experiments. The scenarios summary examined in this study are displayed in Table 1. To meet the recommended conditions by the Preston [25] on the ratio of the pipe diameter $D_p$ to the thickness of the boundary layer $\delta$, the relative amounts of this ratio was calculated in each of the eleven measuring stations by changing the Preston tube diameter and the aspect ratio $B/H$. An example of the surveys at aspect ratios of 2.86, 6.19, and 13.95 is provided in Figure 3. Survey results in all aspect ratios show that the three last measurement stations have the Preston (1954) proper conditions about the installation of Preston tube diameter in ten percent of the thickness of the boundary layer for all four-pipe diameters. Therefore, the average shear stresses of the last three stations were selected as a base for comparison of the shear stress calculated by the Patel and Bechert calibration equations. In Figure 4, the Preston tubes number ($D_p u/\nu \delta$) variations trend versus the aspect ratio is shown. The difference percentage between the shear stress calculated by the Patel and Bechert equations and the aspect ratio for the use of all four Preston tube diameters is shown in this Fig. Apparently, using of 3.9 mm diameter represents the smallest difference between the results of the Patel and Bechert calibration equations.
Using relations (4) and (5), the wall friction coefficient values versus normalized pressure difference values in all aspect ratios were calculated by the Patel and Bechert calibration equations. Figure 5 shows an example of the wall friction coefficient variations versus the normalized pressure difference in aspect ratio of 13.95. Surveying the results of wall friction coefficients also indicates that using of 3.9 mm diameter, represents the smallest difference between the Bechert and Patel calibration equations results for the average shear stress. The results in Figure 5 show that for the use of all different Preston tube diameters, shear stress values obtained from the Bechert calibration equation is bigger than the Patel calibration equation.

Fig 3. Comparison of the ratio of the Preston tube diameter on boundary layer thickness and longitude distribution of shear stress derived from Patel calibration Eq.

Fig 4. Comparison of the difference percentage between shear stress resulting from Bechert and Patel (%Δτ) versus aspect ratio, left coordinate variation trend of the Preston tube number versus aspect ratio

Fig 5. Wall friction coefficient variation versus normalized pressure difference in aspect ratio of 13.95

1-3-2-Results of the transverse shear-stress distribution

Determining the transverse shear-stress distribution in the vicinity of the rectangular channel bed and wall, Preston tubes were moved with a two-dimensional movable seat, adjacent to the wall and bed. The interval of these location changing in the vicinity of the bed and wall, were between 5 and 10 mm. The bed and wall local shear stress was measured and shown in Table 1 for all of the B/H aspect ratios using differential pressure meter of the Preston tube and the Patel calibration curve. Schematic of local bed and wall shear stress distribution is shown in Fig. 6. Figures 7 to 12 show the transverse distribution of local shear stress in bed and wall for aspect ratios of 2.86, 6.19, and 13.95

To facilitate the comprehension of these results, attempts have been made to present the relative parameters as dimensionless form as \( \frac{\tau_b}{\bar{\tau}_b} \) and \( \frac{\tau_w}{\bar{\tau}_w} \). \( \tau_b \) are the local shear stress for the bed and wall, respectively and \( \bar{\tau}_b \) and \( \bar{\tau}_w \) are average shear stress for the bed and wall, consequently.

Laboratory observation revealed that \( \frac{\tau_b}{\bar{\tau}_b} \) and \( \frac{\tau_w}{\bar{\tau}_w} \) has a maximum value and this value occurred in aspect ratios of 2.7 and 1, respectively.

| Table 1 | Experimental results summary |
Non-linear regression equations were used in order to achieve the governing equations of the transverse distribution of local shear stress in the wall and bed, in smooth rectangular channels. For this purpose, the SPSS software was used. Relationship (6) and (7) represent the transverse distribution of shear stress in the bed and wall which became dimensionless by the total shear stress.

\[
\frac{\tau_{b}}{\gamma HS} = \left(1 - 1.1082(B/H)^{-1.3709}\right) \times \text{EXP}\left(0.85 - 0.5922(b/B)^{0.2858}\right)
\]  

\[
\frac{\tau_{w}}{\gamma HS} = \left(1 - 1.9255(B/H)^{-2.4997}\right) \times \text{EXP}\left(-0.3166 - 0.0187(Z/H)^{-0.8415}\right)
\]

In order to verify the accuracy of the results of the relationships (6) and (7), Figures 13 and 14 show the theoretical calculated results of the $\tau_{b}/\gamma HS$ against observed $\tau_{b}/\gamma HS$ data and also show theoretical calculated results of the $\tau_{w}/\gamma HS$ against observed $\tau_{w}/\gamma HS$ data. Statistical analysis of the results predicted by the equations (6) and (7) versus laboratory observations are shown in Table 2. In order to obtain a better understanding, the process of the variations trend of the in relations (6) and (7) versus the aspect ratio and location in cross-section, Figures 15 and 16 show the three-dimensional space procedures of mentioned equations.
Table 2. Error functions resulted from Eq. 6 and Eq. 7 versus experimental observations

Fig 15. Local variations (b/B) of relative bed shear stress $\tau_b/\gamma HS$ versus aspect ratio (B/H)

Fig 16. Local variations (Z/H) of relative wall shear stress $\tau_w/\gamma HS$ versus aspect ratio (B/H)

Procedure depicted in Figure 15 indicates that the B/H aspect ratio is effective on the dimensionless bed shear stress distribution $\tau_b/\gamma HS$. A similar analysis can be seen in Figure 16, which seemingly it has only a minor effect on the of wall shear stress distribution $\tau_w/\gamma HS$ in rectangular open channels.

In order to compare the results of this study with previous researches, laboratory results of Knight et al. [26], Knight and Hamed [27], Myers and Elsawy [28] and Cokjat and Younis [29] have been used. Figure 17 shows the results predicted by Equation 6 versus the results of previous research in the aspect ratio range of 3.91 to 4.74. In Figure 18, the results of relation 7 prediction and the results of the laboratory research of Knight et al. [26], Knight and Hamed [27] and Meyers and Elsawy [28] with B/H aspect ratio in the range of 1.5 to 8 are displayed. Comparing predicted results versus the experimental results of the other researchers suggest that predictions of equation 6 and 7 have a proper consistent with previous experimental researches. The relative independence of the Wall Shear Stress $\tau_w/\gamma HS$ in this comparison is remarkable and striking.

Fig 17. Shear stress distribution in bed of rectangular channels in different studies.

Fig 18. Shear stress distribution in wall of rectangular channels in different studies.

1-4-Discussion

In this section, analysis of the results is carried out in order to design open channels. Open channel design requires knowledge of the shear stress and knowing how to distribute it on the bed and channel wall. In Figure 19, a variation of the maximum shear stress (Derived from laboratory observations of this study) on the bed and wall of rectangular channels is displayed versus the aspect ratio. Expanding the application of the results under different conditions, maximum observed shear stress in the bed and wall became dimensionless using the average stress. Since, observations of this study do not include the aspect ratios smaller than 2.85, the experimental observations and Kartha and Leutheusser [3] are displayed in this figure. All the fitted curves from laboratory observations on the bed and wall can be considered as a realistic criteria and benchmark to be used to design open channels. The results
showed that the bed shear stress $\tau_{\text{max}}/\bar{\tau}$ for the aspect ratio of 2.7 will increase the shear stress to 1.55 times of the average amount. Results also show that in the aspect ratio of 1, close to the wall, $\tau_{\text{max}}/\bar{\tau}$ will increase 1.31 times of the average shear stress. Since the maximum values of the shear stress $\tau_{\text{max}}/\bar{\tau}$ in the vicinity of the wall and the bed is realized in aspect ratios near 2, it can be concluded that the best hydraulic conditions could be a critical requirement for open channel design using shear stress, which should be considered. In an aspect ratio development near 2 of the wall and bed shear stress and are in a critical state. Hence, both of these should be designed as a criterion for consideration. On the other hand, for aspect ratios greater than 2, the amounts of shear stress in the vicinity of the wall tend to be 1, and this suggests that the shear stress should be considered as a standard in channel designing.

1-5-Conclusions

This research was performed to determine the optimal diameter of the Preston tube and aimed to declare the distribution of the wall and the bed local shear stress in smooth rectangular channels. Preston tubes with external diameters of 3.2, 3.9, 4.7, and 6.3 mm were used. Analysis of the uniform conditions variations in aspect ratios of 2.86 to 13.95 were carried out. The results showed that using a pipe with an external diameter of 3.9 mm, presents the minimum difference in the average shear stress derived from the Patel and Bechert calibration equations. For steady flow conditions used in this study, different relations were presented to determine the transverse distribution of shear stress on the bed and wall. These relationships are a function of the $B/H$ aspect ratio, relative coordinates of the bed cross section $b/B$ and walls $Z/H$.

The results showed that both the wall shear stress and the bed shear stress should be considered as an open channel design criterion when the aspect ratio is developing in the neighborhood of 2. Bed shear stress should be considered as a design criterion by the designers for channels with the aspect ratio larger than 3.

The results showed that the dimensionless shear stress distribution is considerably influenced by the aspect ratio. The transverse distribution of stress in the wall will be independent from aspect ratio for aspect ratios greater than 3. For all examined flow conditions in this study, the maximum shear stress was observed mainly in the middle of the channel.

Acknowledgments

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Reference


**Figure Captions**

Fig1. Interaction between secondary flow cells and shear stress distribution in the different aspect ratios, Knight and Pat [4,5]

Fig2. Experiment schematic

Fig3. Comparison of the ratio of the Preston tube diameter on boundary layer thickness and longitude distribution of shear stress derived from Patel calibration Eq.

Fig4. Comparison of the difference percentage between shear stress resulting from Bechert and Patel (\%Δτ) versus aspect ratio, left coordinate variation trend of the Preston tube number versus aspect ratio.

Fig5. Wall friction coefficient variation versus normalized pressure difference in aspect ratio of 13.95

Fig6. Schematics of local coordinates of shear stress distribution in wall and bed of rectangular channel

Fig7. Local shear stress distribution in bed, aspect ratio: 2.86

Fig8. Local shear stress distribution in wall, aspect ratio: 2.86

Fig9. Local shear stress distribution in bed, aspect ratio: 6.19

Fig10. Local shear stress distribution in wall, aspect ratio: 6.19

Fig11. Local shear stress distribution in bed at aspect ratio: 13.95

Fig12. Local shear stress distribution in wall at aspect ratio: 13.95

Fig13. Fitting predicted results of Eq.6 with experimental results for estimating $\frac{\tau_b}{\gamma HS}$

Fig14. Fitting predicted results of Eq.7 with experimental results for estimating $\frac{\tau_w}{\gamma HS}$

Fig15. Local variations ($b/B$) of relative bed shear stress $\tau_b/\gamma HS$ versus aspect ratio ($B/H$)

Fig16. Local variations ($Z/H$) of relative wall shear stress $\tau_w/\gamma HS$ versus aspect ratio ($B/H$)

Fig17. Shear stress distribution in bed of rectangular channels in different studies.

Fig18. Shear stress distribution in wall of rectangular channels in different studies.

Fig19. Variations of $\frac{\tau_{b_{\text{max}}}}{\tau_b}$ and $\frac{\tau_{w_{\text{max}}}}{\tau_w}$ versus $B/H$

**Table Captions**

Table1. Experimental results summary

Table2. Error functions resulted from Eq. 6 and Eq.7 versus experimental observations
Figures

Fig 1

Fig 2
Fig 3

Fig 4
Fig 5

Fig 6

Fig 7
Latral Distribution of Wall Shear Stress @ B/H=2.86

\[ \frac{\tau_{w,\text{max}}}{\tau_0} = 0.989 \]

Fig 8

Latral Distribution of Bed Shear Stress @ B/H=6.19

\[ \frac{\tau_{b,\text{max}}}{\tau_0} = 1.423 \]

Fig 9

Latral Distribution of Wall Shear Stress @ B/H=6.19

\[ \frac{\tau_{w,\text{max}}}{\tau_0} = 0.962 \]

Fig 10

Latral Distribution of Bed Shear Stress @ B/H=13.95

\[ \frac{\tau_{b,\text{max}}}{\tau_0} = 1.226 \]

Fig 11
Fig 12

Latral Distribution of Wall Shear Stress @ B/H=13.95

\[ \frac{\tau_{w_{max}}}{\tau_{w}} = 0.828 \]

Fig 13

\[ y = 0.9712x \]

Fig 14

\[ y = 0.9953x \]
Fig 15

Fig 16

0.0
0.2
0.4
0.6
0.8
1.0
1.2
4
6
8
10
12
0.10.20.30.4
t
b/B
HS

0.0
0.2
0.4
0.6
0.8
4
6
8
10
12
0.20.40.60.8
w/
HS
B/H
Z/H

Knight et al. 1984 (B/H=3.91)
Cokljat et al. 1995 (B/H=3.94)
Knight et al. 1984 (B/H=4.74)
Present Study (B/H=4.51)
### Table 1

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<th>(V(m/s))</th>
<th>(Fr)</th>
<th>(Re \times 10^4)</th>
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<th>(\gamma HS)</th>
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<td>0.66</td>
<td>6.4</td>
<td>0.322</td>
<td>0.442</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>equation</th>
<th>ME</th>
<th>MPE</th>
<th>MAE</th>
<th>RMSE</th>
<th>SEE</th>
<th>CRM</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau_b/\gamma HS)</td>
<td>0.159</td>
<td>-0.149</td>
<td>0.0066</td>
<td>0.0247</td>
<td>0.0688</td>
<td>0.0189</td>
<td>0.9088</td>
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<tr>
<td>(\tau_s/\gamma HS)</td>
<td>0.0448</td>
<td>0.7554</td>
<td>0.0029</td>
<td>0.0094</td>
<td>0.0304</td>
<td>0.0017</td>
<td>0.9707</td>
</tr>
</tbody>
</table>

### Biographies

**Babk Lashkar-Ara** is an Assistant Professor of Civil Engineering at Jundi Shapur University of Technology. He received his PhD from the Shahid Chamran University, Ahwaz, Iran. His research interests include sediment transport, river engineering and hydraulic structures. He has authored and co-authors over 36 papers in reputed National/ International journals and 57 papers in Iranian National/ International conference.

**Masumeh Fatahi** has completed her M.Sc degree in civil engineering from the Jundi-Shapur University of Technology, Dezful, Iran, in 2016. She has authored 2 papers in Iranian National journals. Her research interests include application of intelligent methods in hydraulic engineering, Estimation of local scour in hydraulic structures and Determine of shear stresses in gravel bed rivers.